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Error protection techniques for longitudinal digital recording of audio and video signals

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ERROR PROTECTION TECHNIQUES FOR LONGITUDINAL DIGITAL RECORDING OF AUDIO AND VIDEO SIGNALS

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Summary

Techniques for protection against errors arising during magnetic tape recording of digital audio and video signals are discussed. These errors mostly result from 'drop-outs' which cause burst errors typically affecting several hundred successive bits. The error protection techniques considered include the use of (a) conventional error-detecting and correcting codes employing parity check bits (b) data re-ordering to break up burst errors into shorter groups of errors which are easier to correct (c) the examination of signal characteristics so as to detect errors without employing parity check bits. The report includes general details of error protection methods that have been designed to operate with specific experimental equipment for the recording of digital audio and video signals. Possible improvements in error protection methods for video recording are suggested.

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ERROR PROTECTION TECHNIQUES FOR LONGITUDINAL DIGITAL RECORDING OF AUDIO AND VIDEO SIGNALS

V.G. Devereux, M.A.

1. Introduction

Errors arising during digital recording on magnetic tape are mostly caused by drop-outs. With the high packing densities used in the magnetic recording of audio and video signals, these drop-outs can cause the loss of several hundred successive bits. These burst errors are therefore different in nature from the errors likely to be obtained in digital transmission links, which are more likely to introduce random errors. Methods of protecting against errors caused by drop-outs are influenced by the manner in which the recording tracks are laid down on the magnetic tape. This report is concerned with equipment in which 42 tracks were recorded longitudinally on 25.4 mm (1 inch) wide tape. A feature of this recording format which considerably influenced the design of error protection techniques was that the 0.6 mm spacing between adjacent tracks was greater than the diameter of most drop-outs. As a result, each drop-out normally affected only one track. In addition, more than one track was normally used for a single data channel, and it was therefore possible to break-up the errors caused by a single drop-out into a succession of short duration groups of errors interleaved with error-free data.

It can thus be seen that recording errors have particular features which are unlike those normally occurring elsewhere in a digital system. As a result, the use of relatively unconventional error protection schemes are likely to give the most effective results. A difficulty in designing suitable protection schemes is that no satisfactory method has yet been found for measuring the statistics of recording errors in sufficient detail for accurate theoretical predictions to be made concerning the effectiveness of any given protection scheme and, therefore, experimental verification has been found to be necessary.

The impairment caused by errors in a digital sound or video signal can be reduced by either error correction or error concealment. In error correction, it is necessary to be able to detect the individual bits that are in error; correction is then achieved by changing erroneous bits from 1 to 0 or vice versa. In the case of error concealment, the detection process need not be so precise and could for example merely indicate that an error had occurred in a group of digits corresponding to an audio or video sample. The effect of the errors would then be mitigated by replacing each such erroneous sample by an estimate of its correct value obtained from adjacent error-free samples. Experimental work has indicated that error concealment is more effective in digital video recording than in digital audio recording; with audio recording, the residual impairment caused by inaccuracies in the estimation process is normally too noticeable to be acceptable for high quality purposes. It may be noticed that the possibility of concealment is dependent on the type of signal coding employed. For example, satisfactory results can generally be obtained when concealment is applied to a video signal coded in p.c.m. form, but it generally gives unsatisfactory results with video d.p.c.m. signals, in which a small error in one difference value is added to many successive sample values.

Techniques which may be applied in the detection and correction of recording errors include (a) error-detecting and correcting codes based on the addition of extra check bits, (b) data re-ordering and (c) use of signal characteristics not connected with check bits.

The application of these techniques to digital recording are discussed in Sections 2 to 4. Coding schemes designed specifically for experimental video and sound digital recorders are discussed in Section 5 and also in Refs 1 and 2.

The practical problems involved in protecting against errors in digital recording are somewhat different for video and audio signals due to the difference in bit-rate required for these two types of signal. For video signals, the bit-rate for information bits alone is already very high and it is desirable that any increase caused by parity bits should be as small as possible (e.g. $< 10\%$). For audio signals, this problem is not so severe and it may even be practicable to use more parity bits than information bits.

2. Error detecting and correcting codes

2.1. General

There are two broad classifications of error-detecting and correcting codes, namely, block codes and convolutional codes. In a block code, a specified block of information bits is checked by a set of parity bits which have no connection with other blocks of information bits. In convolutional codes, each block has an associated set of parity bits but these also check the information in a given number of preceding blocks.

It would appear that there are no distinct relative advantages of one class of code over the other for protecting against random single digit errors but, for long bursts of errors, the instrumentation required appears to be much simpler for block codes.

A vast number of error codes have been proposed by other workers.[3,4] Those featuring in this investigation are relatively simple to instrument and were chosen with the particular properties of digital recording systems in mind. Their main features are given below.

2.2. Simple parity protection (block code)

Simple parity protection is a block coding technique in which one parity bit is added to each block of information bits. The state of the parity bit is set to 0 or 1 so that there is always an even (or alternatively odd) total number of 1's in the block. Any odd number of errors in the block will violate this parity rule and therefore the blocks in which such errors occur can be detected but the position of the erroneous bits within the block cannot be determined.

2.3. Hamming codes (block codes)

In the simplest Hamming code,[5] each block of n bits (parity + information) is checked by m parity bits where $2^m \geq n + 1$. This code can correct only single-bit errors in a given code block. Maximum values of n for values of m from 2 to 7 are therefore

No. of parity bits	m	2	3	4	5	6	7
Block length	n	3	7	15	31	64	127

2.4. Cyclic codes (block codes)

The term cyclic code covers a wide variety of block codes which may be used to protect against both single and burst errors.[6] In a given cyclic coding scheme, valid codewords (including both information and parity bits) are those which are divisible, modulo 2, by a fixed binary number P usually referred to as the 'generator' word or polynomial. In this discussion, the term 'codeword' refers to one block of the cyclic code.

A possible, but not the most convenient method, of generating codewords is to multiply the information words by P using modulo 2 arithmetic. If P contains m + 1 bits, the codewords have m bits more than the information words.

Detection of errors is achieved by dividing a received codeword by P, when the remainder will be zero if no errors have occurred. Any burst error of length no greater than the number of parity bits will give a non-zero remainder and will therefore be detected. Also a high percentage of longer bursts will be detected, the fraction which are undetected being approximately 1 in 2^m.

Correction of errors is more difficult than detection and is achieved by examining the value of the remainder after dividing by P. In order for correction to be possible, one necessary condition is that each correctable error pattern should give rise to a different remainder. The above condition indicates that for a single-error correcting code with n bits per block, the maximum possible value of n is equal to $2^m - 1$ since there are n different errors to be corrected and the number of possible non-zero m-bit remainders is equal to $2^m - 1$. For burst-error correcting codes, the maximum value of n will be less than $2^m - 1$.

A second necessary condition for the correction of burst errors of any length up to L bits to be possible is that m should be greater than or equal to 2L.

2.5. Wyner-Ash codes (convolutional codes)

Wyner-Ash[7] codes are convolutional codes similar to the Hamming codes in that they only correct isolated single-bit errors. The coded data is divided into blocks which each contain only one parity bit. For block lengths up to 2^{m-1} bits (parity + information), where m is an integer, the state of each parity bit is given by a simple parity check based on a particular selection of bits occurring in the previous m blocks. A group of m blocks is known as the constraint length of the code. All single-bit errors are corrected provided there is no other error within the same constraint length of $m.2^{m-1}$ data bits which includes m parity bits. Values of the constraint length for values of m from 2 to 7 are

No. of parity bits m	2	3	4	5	6	7
Constraint length $m.2^{m-1}$	4	12	32	80	192	448

Comparison of these figures with those given for the Hamming code shows that the Wyner-Ash code requires slightly less parity bits for the correction of one error in a fixed number of data bits. The Hamming code has the advantage, however, that, for a given ratio of parity bits to information bits, it is less likely, in the presence of random errors, to fail due to uncorrectable error patterns. A more detailed comparison of the two codes is given elsewhere.[8]

3. Data re-ordering

In this process, signal samples are re-ordered in time before recording and the inverse procedure is applied after replay. The aim is to break up long burst errors into a succession of single errors or short burst errors which are easier to conceal or correct than are the original errors.

A block diagram of a system employing error correction and re-ordering is shown in Fig. 1. If no errors have occurred, the data streams at U, V and W are identical to those at Z, Y and X respectively. It will be assumed that

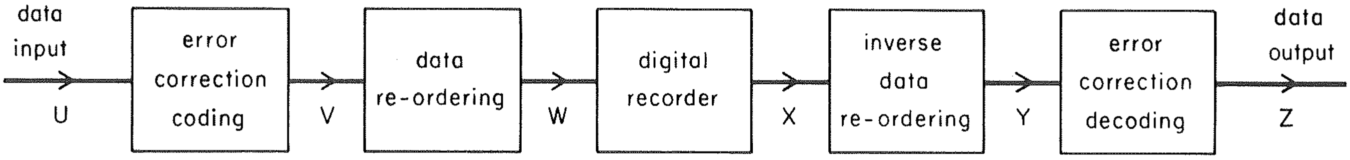

Fig. 1 - Block diagram of burst-error corrector using data re-ordering

a block error correcting code is employed which can correct one error in a block of b bits in the data streams V or Y. This system is required to correct burst errors of length up to B bits occurring in the data stream X obtained from the digital recorder. This means that a burst error of length B in the data stream X must not give more than one error in any block of b bits in the data stream Y.

A convenient re-ordering process involves passing each of the b bits in a block through separate delays of 0, B, 2B, . . . (b—1)B bits. By multiplexing the output data streams from these delays, a single re-ordered data stream is obtained in which adjacent bits from one block are separated by B bits. As a result a burst error of less than B bits only affects one bit from a given block. Further details of the process are given in the Appendix, Section 8.

Re-ordering appears to be most useful when only one track is used per data channel on a digital recorder. When more than one track is used per channel the data can be allocated to the different tracks in such a manner that a single long burst-error on one track results in a series of single-bit or short burst errors in the replayed data and therefore there is less to be gained by the additional use of re-ordering. (See Section 5.2.3.).

The main disadvantages of data re-ordering for correcting errors due to drop-outs are (a) it requires a comparatively large digital store (e.g. 1,000 – 10,000 bits), (b) the maximum length of the error which can be corrected is restricted to a fixed amount proportional to the size of the digital store, and (c) correction is only possible if there is an error-free zone between drop-outs, the length of this zone being equal to the track length over which a code block is spread by the re-ordering process.

4. Use of signal characteristics

Both digital and analogue signals have certain features which may be of assistance in the detection of errors without recourse to parity bits. For example an indication of the presence of errors may be obtained

a) if the amplitude of the replayed digital signal (before slicing) falls below a certain level. A similar technique is used for detecting drop-outs in analogue video-tape recording.

b) if signal transitions in the replayed digital signal occur at random intervals instead of at integer multiples of the clock-pulse period.

c) if the replayed digital signal contains sequences of digits prohibited by the digital code used for recording. For example, with delay modulation, the digital code should remain in the same state for 1, 1½ or 2 clock-pulse periods and therefore an error has occurred if this rule is not observed.

d) if the difference between actual sample values and predictions of these values based on adjacent sample points, is greater than would be expected for a normal video signal.

The advantage of the error detection methods given above is that they do not require the addition of parity bits. Method (c), of course, is also the method used with parity bits.

5. Application to specific requirements

This section describes error protection schemes which have been instrumented or have been proposed for use with specific experimental audio and video digital tape recorders. These schemes are based on the techniques discussed in the previous Sections but in some cases the method of applying these techniques is relatively unconventional since the errors obtained in digital recording have features which are unlike those obtained in other parts of a digital system, as discussed in Section 1.

5.1. Error protection for a digital video recorder

5.1.1. Techniques used

Several different coding schemes have been proposed and/or implemented for use with a digital video recorder employing longitudinal recording along 42 tracks.[1,2,9] Originally two tracks were reserved for parity bits and the other 40 tracks were used to record the different bits of 5 successive video samples, each sample being represented by 8 bits. In the first error protection scheme, each bit on the two parity tracks was used to give simple parity protection of the three most significant bits of a given sample. Only two out of five samples could be protected in this way and these were selected according to a cyclic pattern. With this scheme, it was possible to determine which samples had been affected by a long burst error on one track by examination of the pattern of parity failures.[2] Any errors detected in this way were concealed by replacement with data from nearby sample points. This coding scheme failed to detect about 10% of long burst errors, probably as a result of the overlapping of errors on different tracks; in addition short errors could not be detected. Since this performance was not thought to be good enough, further coding schemes were investigated.

In a second error protection scheme the least significant bit of each sample was replaced by a parity bit giving 5 parity tracks and 35 information tracks.[2] (The original 2 parity tracks were not used). Each parity digit protected the three most significant bits of a single 7 bit sample using a simple parity code. This scheme could detect single errors in addition to burst errors and could also detect simultaneous errors affecting different samples. Detected errors were concealed as in the first coding scheme. The performance of this second scheme was noticeably superior to that of the first scheme, the effect of errors on a television display being only occasionally noticeable.

A third coding scheme used the same parity system as the second but in addition made use of the two extra parity tracks to provide correction of burst errors in the 4 most significant bits of each word instead of only error concealment.[2] A small further reduction in the visibility of errors was obtained.

5.1.2. Possible further techniques

So far no use has been made of signal characteristics as mentioned in Section 4. If one of these techniques could be made to work satisfactorily, it would have the advantage that the track on which an error had occurred could be determined without the use of parity bits; this would mean that burst errors in one track alone could be corrected by means of only one parity track, in which each parity bit applied simple parity protection for code blocks formed from one bit in each of the 40 data tracks.

If errors were detected by examining the signal obtained directly from a replay head, it would be necessary to delay the information concerning errors by the same amount as the delay through the timing corrector incorporated in each of the 40 data channels. In order to overcome this problem, it would probably be helpful if the format of the recorded data were re-arranged so that all the bits of each sample were recorded on a single track. Using this format it would be possible, when errors were detected, to set the data to a forbidden state (such as all zeros) before re-timing. The information concerning errors would then be automatically delayed by the same amount as the data.

An alternative method of making use of signal characteristics would be the comparison of actual and predicted sample values in the final signal obtained after multiplexing the signals from the 40 separate channels.[10] If the data format suggested in the previous paragraph were in use, the fact that all the bits in a sample would be affected by an error in one track would, in general, give large prediction errors which should be easy to detect when many successive samples were in error. With the original data format (as described in Section 5.1.1.), an error occurring in a track handling one of the less significant bits might be difficult to detect by prediction methods. Using the prediction technique in conjunction with one parity track, in which each parity bit is applied to one bit from each of the 40 information tracks, the parity bits would be used initially to detect the presence of an error and the prediction technique would then be used to determine the track that contained the error. The knowledge obtained from both the parity bits and the prediction technique would then be combined to correct the errors. This technique would fail with simultaneous errors in two tracks but, by using two parity tracks, each being applied to half of the information tracks, errors occurring simultaneously in one track from each set would be corrected. Further sub-division would of course be possible if required.

An alternative method of locating the track in which an error had occurred would be to employ a separate error detecting code on each track, as in the orthogonal coding technique described for an audio recorder in Section 5.2.1.

5.2. Error protection for a multichannel digital audio recorder

Work has been carried out to investigate the possibility of using a 42-track longitudinal recorder as a multichannel digital audio recorder. An important requirement of this equipment was that it should be capable of recording at least 10 audio channels simultaneously. Thus, up to four tracks could be used per audio channel. This Section discusses the use of error correcting codes, both with and without data re-ordering for protecting against errors arising in such equipment.

For the error correcting codes with no re-ordering, burst errors of any length in one track are corrected but correction fails if there are simultaneous errors in two or more tracks of one channel. The correction capabilities of the coding schemes including re-ordering are limited further by the conditions that the length of the burst error must not exceed a fixed number of bits determined by the capacity of the re-ordering store and also adjacent burst errors on one track must not be closer together than the number of bits over which a single code block is spread by the re-ordering process.

If possible, for all correction systems, other arrangements should be made to mute the audio signal on the rare occasions when error correction fails.

An important constraint placed on the design of the multi-channel recorder was that each audio channel should have its own independent set of tracks; for example, separate audio channels were not allowed to share a common set of parity check bits. This constraint should always govern the design unless the number of available tracks is so limited that the only way to record the required number of signals with adequate error protection is by multiplexing two or more channels onto one set of tracks.

5.2.1. Techniques not employing re-ordering

(a) Use of cyclic code

Experimental equipment has been constructed which uses 4 tracks per audio channel and employs a cyclic block error-correcting code. Each block in this code contains 14 parity check digits to protect the 13 information bits corresponding to a single sample of the audio signal. The recorded data consists of 7 bits per sample on each of 4 tracks, one spare bit being added per block so that each track contains the same number of bits. The 14 check bits correct errors affecting up to 7 adjacent bits in one block, and therefore, errors of any length affecting only one track are corrected. The performance of this coding technique is very satisfactory for correcting errors in a high quality digital audio signal.

The data format described above is illustrated in Fig. 2 together with the corresponding formats for 3, 5, 6, 7, 10 and 18 tracks per channel. This figure also gives corresponding values of tape speed in inches per second assuming that the audio signal is sampled at 32 KHz and the data packing density for each track is 15K bits/inch; under these conditions, the tape speed in inches/sec is equal to 2·13 times the bits per sample in each track.

Information corresponding to that given in Fig. 2 is reproduced in Column 2 of Table 1.

(b) Use of Hamming code

An alternative method of applying block codes to correct burst errors on any one track of a multi-track recorder is to use a single-error correcting code with a code block consisting of one bit from each track. Fig. 3 illustrates a possible arrangement of the bits corresponding to one audio sample, using this arrangement in conjunction with a Hamming code (see Section 2.3.) for the case of 7 tracks per channel. The number of bits per sample required on one track as a function of numbers of tracks per audio channel is given in Column 3 of Table 1.

No experimental work has been performed using this coding technique.

(c) Use of Wyner-Ash code

Single-error correcting convolutional codes can be applied, in a manner similar to that used with the Hamming block code, by arranging that the group of bits known as the constraint length is formed from one bit from each track of an audio channel. Experimental equipment has been constructed which employs a Wyner-Ash convolutional code (see Section 2.5.) to correct errors in a 4-track recording channel. The resulting constraint length of 4 bits contained 2 check bits and 2 information

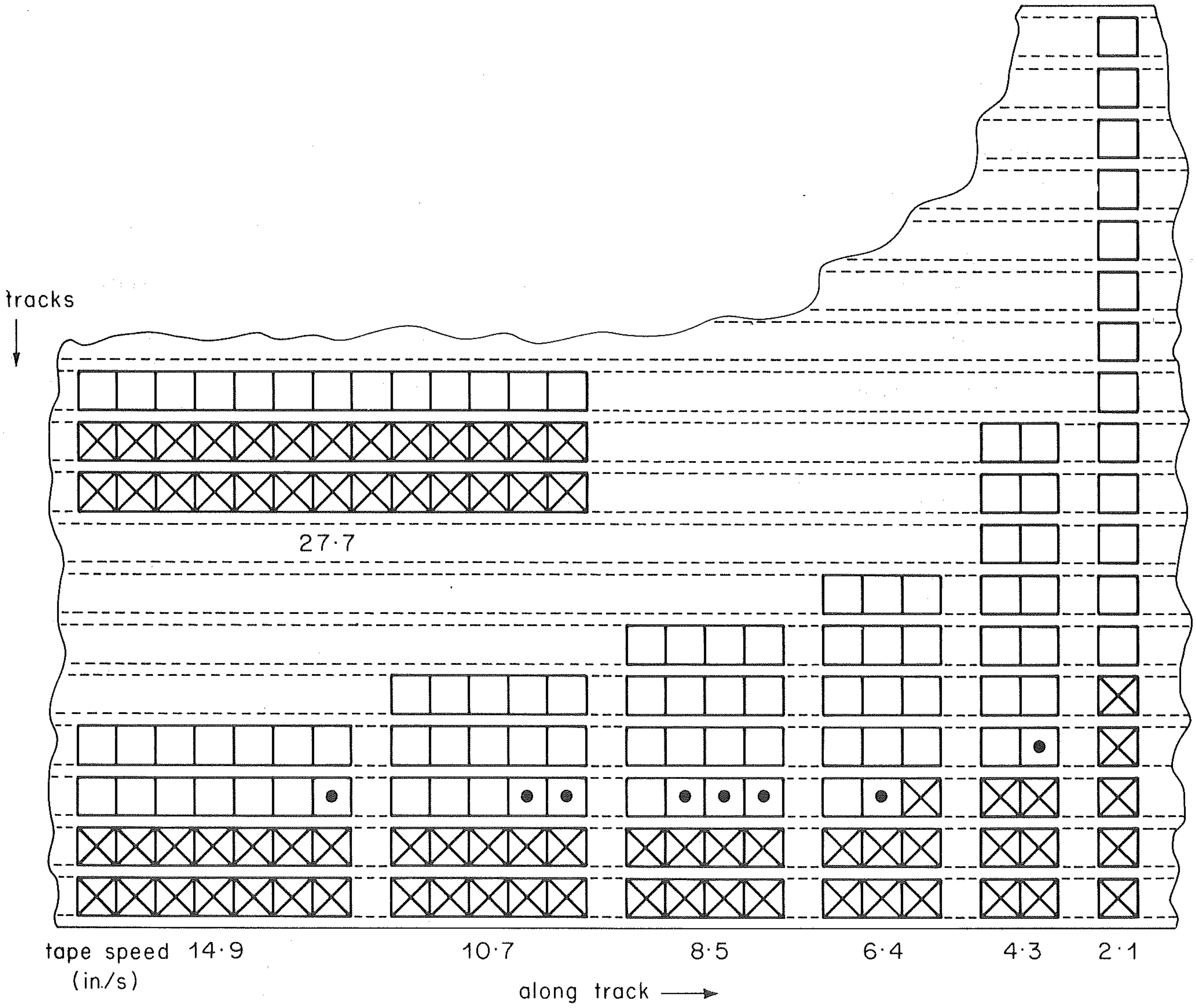

Fig. 2 - Recorded data format for one audio sample using one cyclic code error correcting block per sample. Speed in ins/sec given for 15K bits/inch

☐ information bit ☒ parity bit ● spare bit

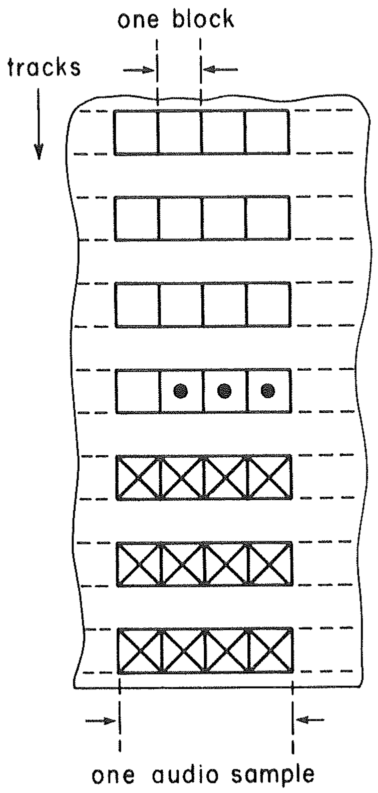

Fig. 3 - Recorded data format for one audio sample using Hamming error correcting code

☐ information bit ☒ parity bit ⊡ spare bit

bits and therefore the arrangement of bits corresponding to one sample could be identical to that shown in Fig. 2 for the cyclic code with 4 tracks per channel. The performance of this error correction system was as satisfactory as the 4-track system using the cyclic code.

Since the instrumentation required for this Wyner-Ash code with 4 bits per constraint length is much less complex than that required for the 4-track cyclic code, which had 28 bits per block, the Wyner-Ash code would appear to be preferable when 4 tracks are available per channel. The number of bits per sample along each track for other numbers of tracks per channel with a Wyner-Ash code in use are given in Column 4 of Table 1.

Note that it is not possible to use the cyclic, Hamming or Wyner-Ash coding schemes with less than three tracks per channel.

(d) Use of orthogonal coding scheme

In the orthogonal error-correcting scheme to be described, one track is devoted to simple parity protection with corresponding parity blocks lying across the recording tracks; in addition, a cyclic coding scheme is employed with code blocks lying along each recording track. This scheme is similar to the prediction scheme outlined in Section 5.1.2., with the difference that a cyclic code is used in place of the prediction technique.

As an example, the data format for an orthogonal coding scheme applicable to three tracks per audio channel is illustrated in Fig. 4. In this figure, the bits marked I_1 to I_{13} represent the 13 bits from one audio sample; the bits marked P_1 to P_7 are simple parity check bits where the state of each of these bits is determined by the state of the two information bits lying immediately above. The groups of m bits marked with an X are error check bits corresponding to a cyclic code. A cyclic code is employed separately for each track, the block length being n bits which covers N samples of the audio signal.

On replay, the signals from the three tracks are fed to three separate cyclic-code error-decoders which are required to detect but not correct any errors that are present. Having established which of the tracks contain errors, assuming that any group of N samples does not contain errors on more than one track, error correction can be achieved since the parity protection scheme employing bits P_1 to P_7 locates the bit positions along the track in which errors have occurred.

It should be noted that, unlike previous schemes described in this Section, orthogonal coding may be applied to only two tracks per audio channel. In this case, the parity protection may be achieved by simply repeating the digital audio signal on the parity track. An experimental 2-track system of this type has been constructed and found to give satisfactory error protection. For this system, 16 check bits were used in one block of the cyclic code to protect 1016 information bits.

The main advantages of orthogonal coding, compared to the coding schemes given earlier in this Section, are, first, it can be applied to only two tracks per channel and, secondly, it gives a reduced number of bits per sample along one track, as indicated by Column 5 of Table 1. The figures in Column 5 have been calculated for $n = 1032$ and $m = 16$, these being the values of n and m selected for use in the experimental 2-track system. The main disadvantages of orthogonal coding compared to previous techniques are a small increase in the number of errors remaining uncorrected and an increase in instrumental complexity; both disadvantages are mainly due to the long block lengths that are required when n and m are suitably adjusted to provide an efficient error correction scheme.

With these orthogonal coding schemes, errors cannot be corrected if there are simultaneous burst errors in two or more tracks or if the cyclic code fails to detect a burst error on one track due to the burst error being divisible by the cyclic code generator word. The proportion of burst errors which are divisible by the generator word is 1 in 2^m and therefore the value of m should be large enough to reduce these undetected errors to a negligible amount.

5.2.2. Application of re-ordering

The basic principles of re-ordering have already been described in Section 3 with further details being given in the Appendix, Section 8.

TABLE 1

Comparison of various correcting codes for a multi-channel recorder. All codes correct burst errors in one track only

No. of Tracks T	Bits per sample along track (α tape speed)					
	No re-ordering				With re-ordering	
	Cyclic code	Hamming code	Wyner-Ash	Orthogonal code	Hamming code E = 1	Burst corrector E = 4
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7
1	–	–	–	–	18 (17B)*	21 (5B)
2	–	–	–	13·2	9 (16B)	11 (5B)
3	13	13	13	7·1	6 (15B)	7 (4·5B)
4	7	13	7	5·1	5 (16B)	6 (5B)
5	5	7	7	4·1	4 (15B)	5 (5B)
6	4	5	5	3·0	3 (12B)	Re-ordering not required
7	3	4	4	3·0	3 (14B)	
8	3	4	3	2·0	3 (16B)	
9	2	3	3	2·0	2 (9B)	
10	2	3	2	2·0	2 (10B)	

* Figures in brackets indicate storage capacity required where B = maximum length of error which can be corrected

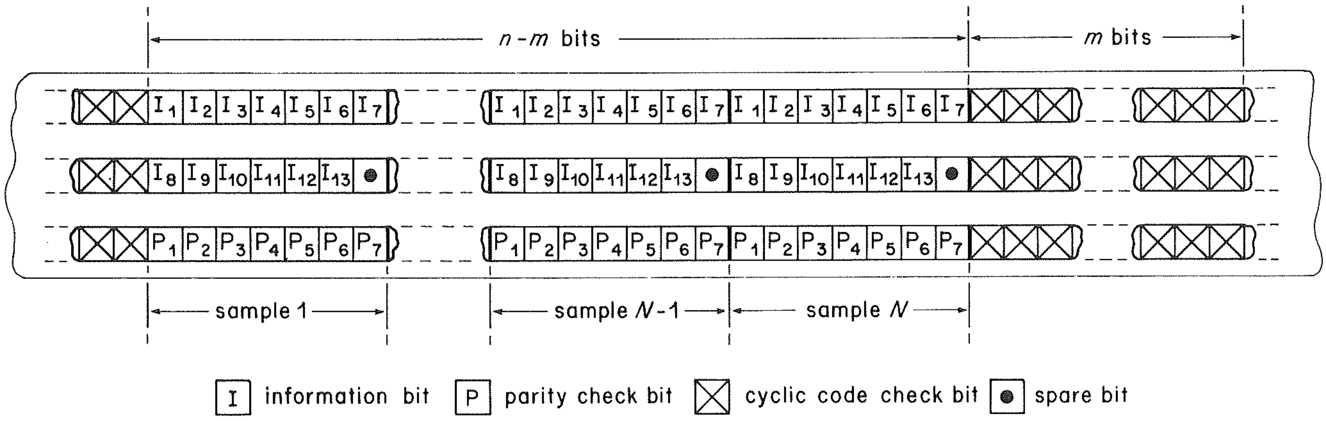

Fig. 4 - Recorded data format for orthogonal coding scheme with three tracks per channel

In the first experimental work on re-ordering, the effects of errors in a digital audio signal that had passed through a re-ordering system were mitigated by means of error concealment rather than by error correction techniques. It was found, however, that the residual noise caused by inaccuracies in the concealment process was too noticeable to be acceptable.

In further work to examine the usefulness of re-ordering in conjunction with error correction, a system was constructed in which a separate re-ordering process was applied to each track of an audio recording channel employing 3 tracks. The error correction code used was a Hamming code which corrected single errors in a block of 18 bits, consisting of 13 information bits from one audio sample and 5 check bits. If the re-ordering process were omitted, the bits in one block would have been recorded in the format shown in Fig. 5(a), the bits in one block being indicated by the numbers 1 to 18. It is not important which bits convey information and which are parity bits. After applying separate re-ordering processes to each track, the resulting data format on the recording tape was as shown in Fig. 5(b). The heavily outlined bits correspond to bits associated with one audio sample, i.e. sample N. To obtain this format, the first step in the re-ordering process was to pass the 6 bits from each sample to be recorded on one track through separate delays of 0, B, 2B, 3B, 4B and 5B, where B was the maximum length of burst error to be corrected; in practice B was chosen to be 300 bits. After this, the six delayed data streams were multiplexed to form a single data stream in which the bits from one sample on any track were separated by B bits. Since burst errors of length B or less bits could not affect more than one bit from any given sample, such errors could be corrected by the Hamming error decoder operating on the data stream obtained after inverse re-ordering.

Although this re-ordering scheme gave a noticeable error reduction, the residual uncorrected errors were too frequent, by a factor of at lease 10:1, to be acceptable for a broadcast-quality audio channel.

The number of bits per sample along one track for a similar error correction and re-ordering process, but with various numbers of tracks per audio channel, are given in Column 6 of Table 1. It has been assumed that the number of bits per sample has been increased where necessary by the addition of spare bits so that each track contains the same number of bits per sample. The figures in brackets in Column 6 indicate the total storage capacity in bits required by the re-ordering process calculated from the expression (b—T) B/E given in the Appendix, Section 8, where b is the number of bits per error-correction code-block, T is the number of tracks per channel and E is the maximum number of consecutive errors in one code block which can be corrected. In the above example, b = 18, T = 3 and E = 1.

The expression (b—T) B/E indicates that the storage capacity can be reduced by increasing the value of E. It should be noted that the storage capacity is not exactly inversely proportional to E, since an increase in E requires an increase in the number of check bits resulting in an increased value of b.

As an example of the effect of increasing E, a cyclic code which can correct four consecutive errors (i.e. E = 4) requires 8 parity bits to protect 13 information bits giving a block size of 21 bits. The resulting number of bits per sample along one track, and the storage capacity for different numbers of tracks per channel, are given in Column 7 of Table 1. For 6 or more tracks per channel, re-ordering is not required because there would be four or less bits per sample along one track and therefore errors on one track only would be corrected without re-ordering.

A further advantage of increasing E is a reduction in the probability of errors remaining uncorrected, this probability being approximately proportional to $(b/E)^2$. Hence the use of the scheme given above with E = 4 should reduce the final error rate to about one tenth that obtained for E = 1 and this might be found to be acceptable although it has not be verified experimentally. The use of E = 1 is inefficient because five parity bits are required per audio sample whereas the use of only three more parity bits per sample enables errors affecting four consecutive bits (E = 4) to be corrected. (See Table 2 in the Appendix, Section 8). This advantage obtained by increasing E arises because the track length over which one code block is spread reduces as E increases and therefore the probability of two separate errors affecting one sample decreases.

The disadvantages of increasing E are, first, an increase in the number of bits per sample due to the extra check bits, and, secondly, a small increase in instrumental complexity.

It may be noted that a re-ordering process can be employed after any of the error correction systems mentioned in Section 5.2.1. in order to reduce the number of tracks per channel. The process involves passing the data corresponding to different tracks through separate delays of 0, K, 2K . . . . . . bits where $K \gtrless B$ and then multiplexing the outputs of these delays.

5.2.3. Comparison of different coding schemes

If only one track is used per audio channel, then the only error correcting schemes that can be employed, of those indicated in Table 1, are those which involve re-ordering. In addition, as mentioned in the last paragraph of the previous Section, a re-ordering process could be applied in conjunction with any of the other multi-track schemes to produce a single track system.

For two tracks per audio channel, either re-ordering (Columns 6 and 7 of Table 1) or orthogonal coding (Column 5) can be employed. Although re-ordering has the advantage that it requires slightly fewer bits per sample, experimental work has indicated that the re-ordering system of Column 6 (E = 1) would not have a very acceptable error correction capability. On the other hand, the performance of the orthogonal system which has been constructed for two tracks was very satisfactory. The performance of re-ordering with E = 4 (Column 7) has not been examined but theoretical work indicates that

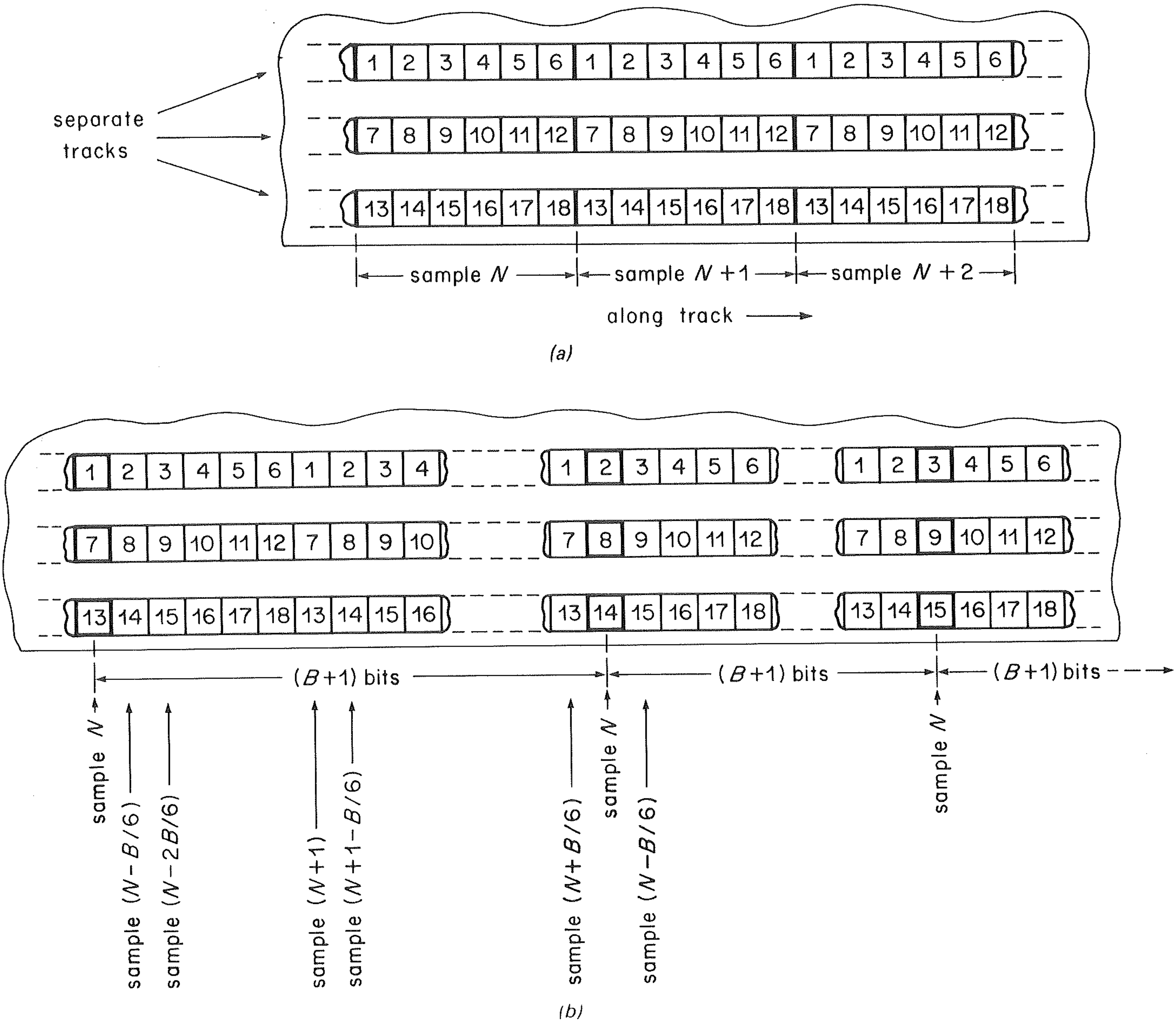

Fig. 5 - Effect of re-ordering process on recorded data format

(a) Format if re-ordering omitted, (b) Format after re-ordering.

it is likely to be slightly worse than orthogonal coding, but significantly better than re-ordering with E = 1.

For three tracks per channel, the optimum choice of code depends on whether the most critical factor is good error correction performance or low tape consumption. The cyclic, Hamming and Wyner-Ash codes of Columns 2, 3 and 4 should all give very satisfactory error correction performance but their tape consumption is nearly twice that required for the orthogonal and re-ordering codes of Columns 5, 6 and 7. However, the codes of Columns 5, 6 and 7 would leave more errors uncorrected, the code of Column 6 being the least satisfactory from this point of view. Further experimental work is required to determine whether the error correction performance of the codes of Columns 5 and 7 would be acceptable although work carried out on the two-track code in Column 5 indicates that the corresponding three-track code is likely to be satisfactory.

It may be noted that a similar error correction performance and tape consumption to those of the 3-track codes in Columns 2, 3 and 4 could be obtained by simply making three identical recordings of the audio signal on separate tracks using no error correction bits, and assuming that if any two replaced signals are identical, then they give the required output signal.

For four tracks per channel, the Wyner-Ash code of Column 4 appears to be the most suitable since the instrumentation required is far less complex than all the other codes, except the Hamming code of Column 3, and the number of bits per sample along a track is much lower than for the Hamming code. An experimental 4-track Wyner-Ash coding system which has been constructed had an acceptable error correction performance.

At the present time, insufficient work has been carried out for definite recommendations to be made concerning the optimum choice of code for more than four tracks per channel. However there does not seem to be any point in employing re-ordering since a similar effect has already been achieved by the use of a large number of tracks per channel.

One possible technique suitable for a large number of tracks per channel which has not been mentioned previously has been described elsewhere.[11,12] This method required about the same ratio of information bits to check bits as the cyclic code described in Section 5.2.1, but appears to have the advantage of simpler implementation. A further advantage, when compared to the cyclic code, is that it not only unconditionally corrects continuous errors in one track but it can also correct errors in two tracks if the signal characteristics (see Section 4) are used to determine which tracks are in error.

6. Conclusions

Various techniques have been described for protecting against errors caused by drop-outs in the magnetic tape recording of digital audio and video signals on one or more longitudinal tracks. It has been shown that the optimum technique depends on various recording system parameters such as the number of tracks to be used per channel, the required tape speed, the probable error rate etc. The practical work carried out so far indicates that satisfactory protection against errors can be obtained by using any one of several different techniques.

In digital television recording, satisfactory error correction is more difficult since there is a much greater premium on bit rate. Nevertheless a reasonable protection against errors has already been achieved, but further improvements are desirable to remove completely all perceptible traces of error.

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8. APPENDIX

Details of re-ordering process

A block diagram of one method of re-ordering a data stream so as to break up burst errors in a recording channel into a large number of single errors is shown in Fig. 6. This diagram is drawn for the case where the preceding error corrector (see Fig. 1) has a block length b of 4 bits. A corresponding timing diagram is shown in Fig. 7. In both Figs. 6 and 7, it is assumed that the 4 bits in each block of the input and output data (V and Y in Fig. 1) are in parallel form and there are fs blocks/sec, while the re-ordered data stream in the recording channel is in serial form at a clock frequency of 4fs bits/sec. B is the maximum length of burst error to be corrected. Since the delay caused by B/4 stages of a shift register clocked at frequency fs corresponds to a delay of B bits in the serial data with a clock frequency of 4fs, it can be seen that the bits from a given block in the input data are separated by (B + 1) bits in the re-ordered serial data stream, an extra 1 bit of delay being introduced by the parallel-to-serial converter. As a result, a burst error of length B bits introduced by the digital recorder into the serial data X causes only one error in any given block of the parallel data Y obtained after inverse re-ordering.

The inverse re-ordering process puts the data back into parallel form and provides suitable delays so that the total delay introduced by the re-ordering and inverse processes is the same for all bits.

The total number of shift register stages required in the re-ordering process is (b—1) B/2 bits; the inverse procedure requires the same number of stages.

A reduction in the number of shift register stages required for a given maximum error length B may be achieved by employing an error correcting code which will correct more than one error in a block. If E is the number of errors per block which can be corrected, the bits in each block need only be separated by B/E bits in the re-ordered data; the total storage required in the re-ordering and inverse procedures is then equal to (b—1) B/E bits.

The disadvantages of reducing the storage by increasing E are that the ratio of parity bits to information bits is increased for a given block size; and the complexity of the error correcting circuits is increased. For protecting against E errors in a block caused by a single burst error, the number of check bits required can be minimised by selecting an error correcting code which only corrects E errors if they occur in adjacent bits in the block.

As an indication of the effect of using an error code capable of correcting E consecutive errors, Table 2 gives

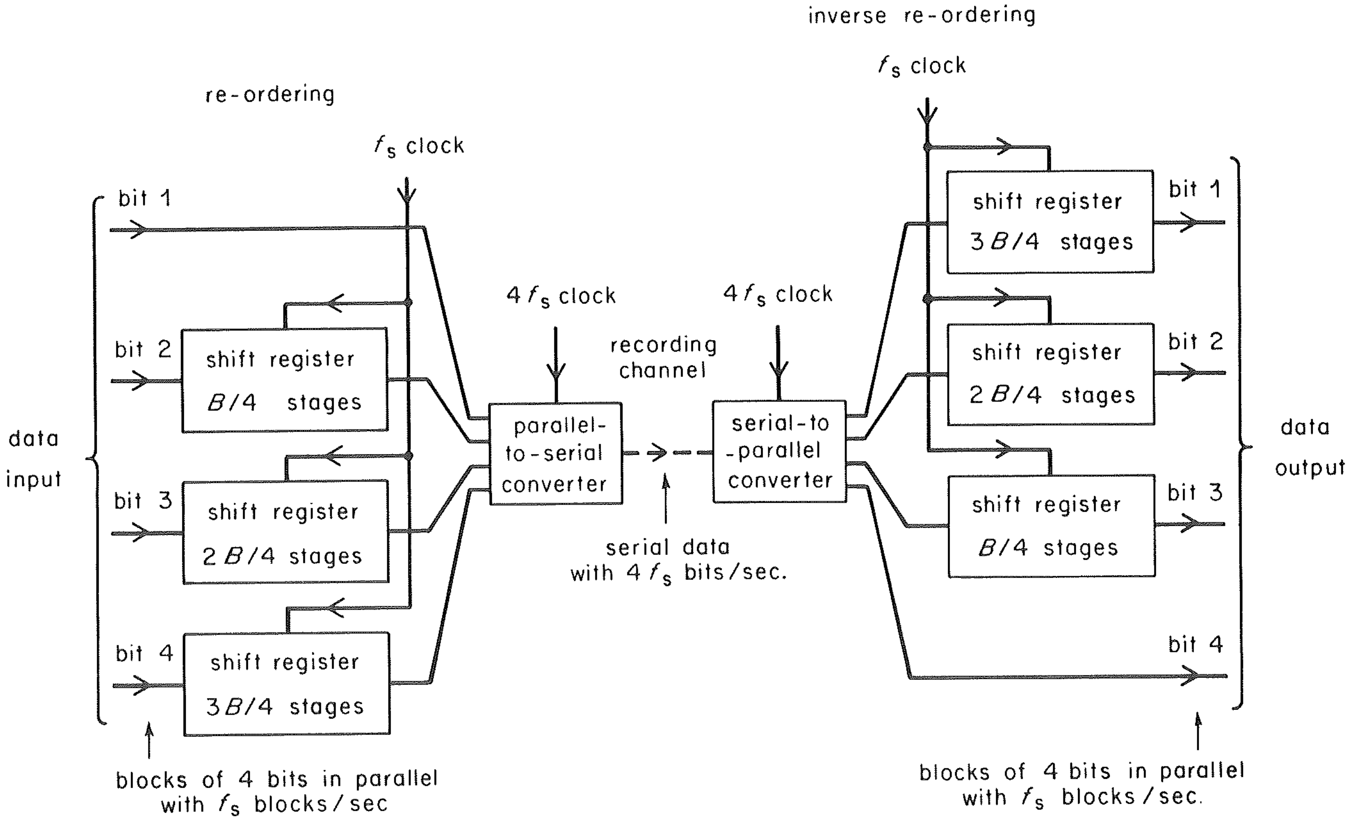

Fig. 6 - Block diagram of re-ordering equipment; 4 bits per error correction block

the number of parity bits P required for various values of E and for a block containing 13 information bits (i.e. the number of bits commonly used in p.c.m. for one audio sample); Table 2 also gives the block size b = (P + 13) and the total storage capacity (b – 1) B/E required by the re-ordering system.

TABLE 2

Details for multiple-error corrections with re-ordering – 13 information bits per block

No. of errors corrected E	1	2	3	4	5	10
Parity bits per block P	5	6	7	8	10	20
Total bits per block b	18	19	20	21	23	33
Total storage (b–1) B/E	17B	9B	6·7B	5B	4·4B	3·2B

Convolutional codes can also be employed in conjunction with re-ordering. The value of 'b' is then equal to the constraint length of the code.

Re-ordering appears to be most useful when only one or two tracks are used per data channel on a digital tape recorder. (See Section 5.2.3.). As mentioned previously, the use of several tracks per channel also breaks up burst errors and therefore there is less to be gained by the additional use of re-ordering.

If T tracks were used per channel and the block of b bits protected by one set of parity bits consisted of b/T bits on each of these T tracks, then the total storage required using separate re-ordering processes for each track would be equal to (b–T) B/E bits. It can be seen that if b $\gg$ T, the storage required is not significantly affected by the value of T, but the tape speed is reduced to 1/T of its value with one track per channel.

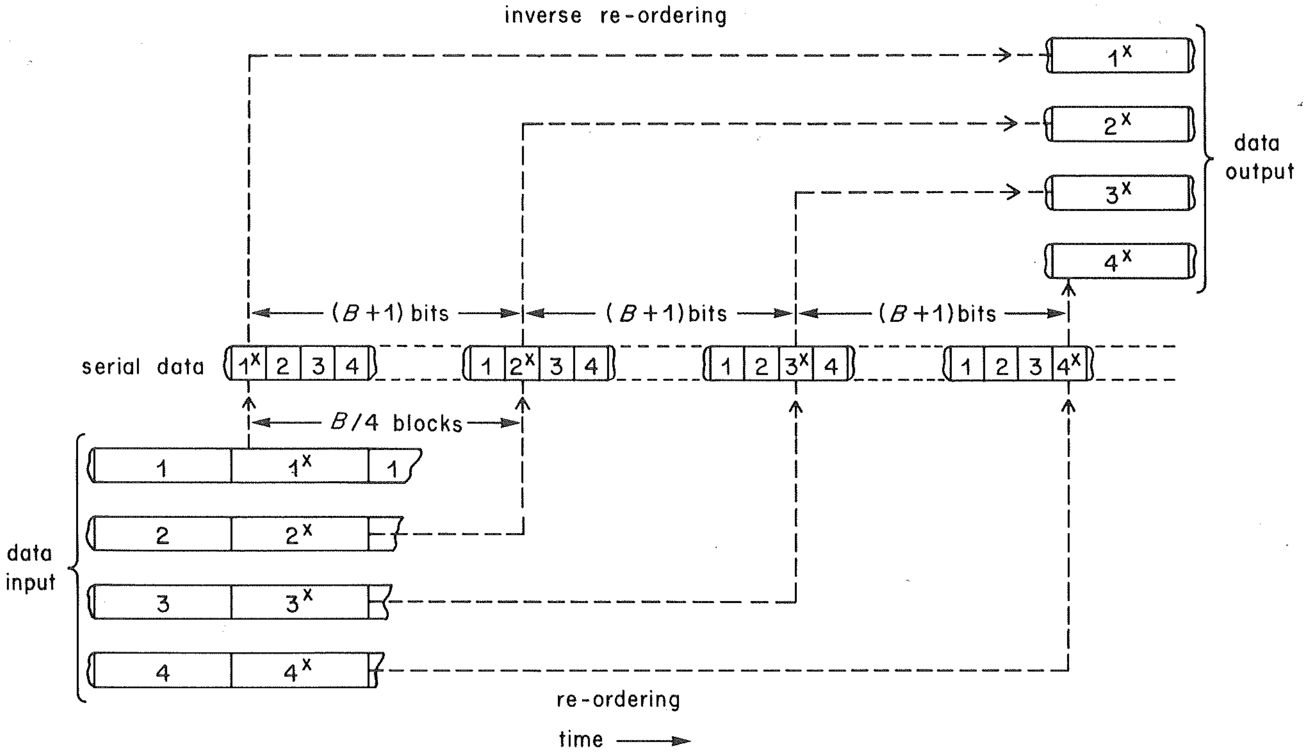

Fig. 7 - Diagram showing delays introduced by re-ordering and inverse process with 4 bits per block

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